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Expectancies modulate attentional capture by salient color singletons

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Abstract

In singleton feature search for a form-defined target, the presentation of a task-irrelevant, but salient singleton color distractor is known to interfere with target detection [Theeuwes, J. (1991). Cross-dimensional perceptual selectivity. *Perception & Psychophysics, 50*, 184–193; Theeuwes, J. (1992). Perceptual selectivity for color and form. *Perception & Psychophysics, 51*, 599–606]. The present study was designed to re-examine this effect, by presenting observers with a singleton form target (on each trial) that could be accompanied by a salient) singleton color distractor, with the proportion of distractor to no-distractor trials systematically varying across blocks of trials. In addition to RTs, eye movements were recorded in order to examine the mechanisms underlying the distractor interference effect. The results showed that singleton distractors did interfere with target detection only when they were presented on a relatively small (but not on a large) proportion of trials. Overall, the findings suggest that cross-dimensional interference is a covert attention effect, arising from the competition of the target with the distractor for attentional selection [Kumada, T., & Humphreys, G. W. (2002). Cross-dimensional interference and cross-trial inhibition. *Perception & Psychophysics, 64*, 493–503], with the strength of the competition being modulated by observers' (top-down) incentive to suppress the distractor dimension.

Keywords: Attentional capture; Oculomotor capture; Singleton distractor interference; Top-down modulation; Cross-trial priming

1. Control of attention in singleton feature search

While it is generally accepted that stimulus- and goal-driven mechanisms of attention can influence target detection in visual search, there has been a great deal of interest recently in whether and how these mechanisms interact with each other in singleton feature search. While some researchers have claimed that salient feature singletons automatically capture attention (e.g., Theeuwes, 1992), others have proposed that bottom-up attentional capture by salient feature singletons is modulated by top-down attentional set (e.g., Bacon & Egeth, 1994; Folk, Remington, & Johnston, 1992).

1.1. Attentional capture and visual salience

Our ability to direct visual attention to goal-defined target features has been investigated in a number of studies (e.g., Pashler, 1988; Theeuwes, 1991, 1992). For example, in Theeuwes' (1991) Experiment 2, there could be two feature singletons, one unique in form (e.g., circle) and one unique in color (e.g., red) amongst homogeneous non-target items (e.g., green squares). One singleton (e.g., the unique form item) was defined as the task-relevant target, and the other as irrelevant distractor (the unique color item). For half of the observers, the target was a form singleton and the distractor a color singleton, and vice versa for the other half. Search performance in these distractor conditions was compared to performance in no-distractor conditions in which the target was always a single unique form or, respectively, color item. Observers' task was to

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respond to the orientation of a line located inside the target singleton. At the beginning of the experiment, observers were informed about the target's defining dimension (e.g., form) and that the presence of an additional feature singleton (e.g., color distractor) would be irrelevant to the task. Distractor presence was manipulated block-wise and the distractor singleton, if present, appeared always at a location different from the target location. Note that the color singleton was more salient than the form singleton (i.e., the former was detected faster than the latter in no-distractor conditions). Theeuwes hypothesized that, if search for a singleton target is guided purely by bottom-up saliency, then a color distractor (more salient) should interfere with detection of the form target (i.e., RTs should be slower for distractor compared to no-distractor trials); in contrast, a form distractor (less salient) should not interfere with detection of a color target (i.e., RTs should be comparable between distractor and no-distractor trials). The results agreed with this pattern. These, and other, findings led Theeuwes (1991), Theeuwes (1992) to conclude that visual selection in singleton feature search is purely bottom-up controlled: attention is automatically captured by the most salient feature in the search array. That is, selection is uninfluenced by top-down factors—because, in search for a form singleton, observers were unable to overcome the detrimental effect associated with the appearance of a salient color distractor. Subsequently, these results have been replicated and extended in several studies (e.g., Bacon & Egeth, 1994; Folk et al., 1992; Jonides & Yantis, 1988; Kumada & Humphreys, 2002). Critically, however, these studies found that salient feature singletons do not necessarily capture attention when they are irrelevant to the task—which has led to various revisions of Theeuwes' automatic-capture account.

1.2. Feature singletons do not always capture attention

For instance, in a series of experiments modeled after those of Theeuwes (1991, 1992) and Bacon and Egeth (1994) observed that the (color) distractor interfered with the detection of the (form) target only when the target itself was also a feature singleton. In contrast, when the (form) target was not unique with respect to its defining feature, that is, when single-target trials were intermixed with two- and three-target trials (multiple targets were form-identical: circles amongst diamond non-targets), the singleton color distractor no longer caused interference. This suggests that salient feature singletons do not necessarily capture attention. Replacing the notion of automatic-capture, Bacon and Egeth proposed that attentional capture by feature singletons is dependent on observers' chosen search strategy: when the target is a feature singleton (as in Theeuwes' studies), it may be beneficial for observers to adopt a singleton search mode, in which they will look for any singleton. This strategy would then also allow a salient singleton distractor to interfere with target detection. In contrast, when the target is not a feature singleton, observers may adopt a feature search mode, in which visual selection can be confined to a specific (target) feature, preventing the distractor from interfering with target detection. A related proposal has been made by Folk et al. (1992), who argued that attentional capture by salient, but irrelevant singletons is contingent on feature- or dimension-based (top-down) attentional control settings adopted to implement the task instruction (contingent-capture account).

More recently, Kumada and Humphreys (2002) proposed an alternative account for singleton distractor interference, namely in terms of cross-trial inhibitory priming. Under conditions similar to those of Theeuwes (1992), Kumada and Humphreys found that, when the trial N form singleton target was presented at the location of a trial $N-1$ color singleton distractor, search RTs were lengthened by some 30 ms relative to the presentation of the target at the location of a previous 'neutral' distractor of the same color as the target. This inhibitory effect was observed both when a distractor was presented on each trial (i.e., 'pure' presentations) and when only half the trials contained a distractor (i.e., 'mixed' presentations). Importantly, with mixed presentations, RTs were hardly different between trial N distractor and no-distractor trials. In this (mixed) condition, a distractor or no-distractor trial N was equally likely to be preceded by a distractor or no-distractor trial $N-1$, so that inhibitory priming would have influenced both distractor and no-distractor trials N (reducing RT differences between the two types of trial). On this basis, Kumada and Humphreys proposed that cross-trial inhibitory priming, rather than within-trial attentional capture, largely accounts for the observed RT pattern and the singleton distractor interference effect in general. That is, cross-dimensional distractor interference results from the competition, on a given trial, between the singleton target and distractor for attentional resources, with selection of the target being accompanied by positional distractor inhibition (e.g., Humphreys & Müller, 1993; see also Müller, von Mühlenen, & Geyer, 2007) which is then carried over to the next trial.

In summary, prior results in the literature are equivocal with regard to whether feature singletons do or do not capture attention and to the mechanism(s) to which the interference effect can be attributed. Bacon and Egeth (1994) reported evidence that singleton distractors can be ignored when the target itself is not a feature singleton. In contrast, when the target is a singleton, singleton distractors may interfere with target discrimination (e.g., Theeuwes, 1992). These contrasting findings have led to the assumption of different attentional control settings (Bacon & Egeth, 1994; Folk et al., 1992): (i) a feature search mode, in which observes deliberately adopt an attentional control set for a specific target feature, which prevents a singleton distractor defined by some other feature (in another dimension) from affecting RTs; and (ii) a singleton detection mode, in which observers allow focal attention to be drawn to the most salient feature in the display; in this mode, sin-

gleton distractors (defined in another dimension than the target) may interference with target detection, with the magnitude of interference is dependent on relative stimulus saliency.

Another account, which makes specific predictions with regard cross-dimensional singleton distractor interference, predicts that stimulus-driven deployment of attention may be top-down modulated even when observers operate in singleton detection mode (Müller, Reimann, & Krummenacher, 2003; Müller, Krummenacher, & Heller, 2004). In particular, Müller et al. (2003) suggested that, in cross-dimensional visual search for singleton feature targets (i.e., when the singleton target can be defined, variably across trials, by either color or orientation, for example), the system automatically 'weights' the coding of saliency signals in the current target-defining dimension, with the weight set implementing a bias to expect a same-dimension target on the next trial (e.g., Found & Müller, 1996; Müller, Heller, & Ziegler, 1995). This bias can be (to some extent) top-down modulated—for example, when observers are provided with an advance cue informing them of the likely dimension of the target in the impending search display. Applied to the singleton distractor paradigm, this would predict that, the greater the weight intentionally assigned to, for example, the form dimension, the less the interference produced by a color distractor. However, the top-down weight set may not completely, or always, overcome distractor interference, particularly when the distractor is more salient than the target. The essential idea of this 'dimension-weighting account' is, similar to the contingent-capture hypothesis proposed by Folk and colleagues (e.g., Folk & Remington, 2006; Folk et al., 1992), that essentially 'pre-attentive' saliency coding processes are themselves subject to 'attentional' modulation (see Müller & Krummenacher, 2006, for a discussion).

On this account, the distractor interference effects demonstrated the studies reviewed above may represent only one end of a continuum of top-down attentional control, where distractor interference can simply not be down-modulated below some minimum value. However, towards the other end of the continuum, the amount of interference may vary with the degree of top-down control applied. This hypothesis seems reasonable, given that previous studies (e.g., Theeuwes, 1991) used conditions in which a distractor was always presented in (distractor) blocks of trials, providing maximum incentive for observers to apply top-down distractor suppression (as well as maximum opportunity to acquire effective suppression routines). Conceivably, however, there would be scope for larger interference effects under conditions in which distractors are not presented on all trials, which would provide less incentive to employ distractor suppression. In summary, assuming that distractor interference depends on observers' incentive to adopt a top-down suppression strategy, then one would expect the magnitude of interference to be greater when distractors are presented on only a small, as compared to a large, proportion of trials within blocks.

2. Experiment

In more detail, the aim of the present experiment was twofold: to examine (i) whether distractor interference in singleton feature search is top-down modulable and (ii) to which mechanism(s) the interference effect may be attributable. Concerning the former, in the current experiment, the presence of the color singleton distractor was manipulated trial-wise (Kumada & Humphreys, 2002) rather than block-wise (Theeuwes, 1991), with the proportion of distractor to no-distractor trials systematically varying across blocks: a distractor was present in either 20%, 50%, or 80% of the trials in a block, that is absent in 80%, 50%, and 20% of the trials, respectively (i.e., 20%-, 50%-, and 80%-distractor conditions). It was expected that, if distractor interference can be modulated intentionally by the observer's incentive to suppress distractors, then larger interference effects should be observed in conditions with a small proportion of distractors (e.g., in the 20%-distractor condition, providing observers with little incentive to adopt a suppression strategy) compared to conditions with a high proportion of distractors (e.g., in the 80%-distractor condition, providing a high incentive to suppress distractors).

In addition to manual RTs, oculomotor performance was analyzed to permit a more detailed investigation of the mechanism(s) that potentially underlie the distractor interference effect. Theoretically, the interference effect could be conceptualized in several ways: first, salient singleton distractors may provide a strong attractor for focal attention, producing a strong tendency to direct the eyes to the distractor location (attentional-engagement hypothesis). On this hypothesis, one would expect that more initial eye movements (saccades) are directed towards the singleton distractor, rather than towards the target. Second, even if the first saccade is not more often directed to the singleton distractor overall, when such a saccade occurs and the distractor is fixated, it may be more difficult for the eyes to disengage from its location (attentional-disengagement hypothesis). On this account, one would expect the eyes (fixations) to remain longer at the singleton than at a 'neutral' distractor location. Third, distractor interference may result from covert deployments of attention, rather than overt movements of the eyes (covert-attention hypothesis). This does, of course, not rule out that observers do not move their eyes in singleton feature search; however, fixation location and duration measures may be inadequate to characterize the distractor interference effect. If the interference effect is due to competition between the target and distractor for attentional selection (e.g., Kumada & Humphreys, 2002), the most apt measure to quantify competition would be the latency of the first saccade. Accordingly, the covert-attention account would predict that it takes longer for the eyes to move in the presence, versus the absence, of a singleton distractor. See also Table 1 which summarizes the predictions of the three hypotheses. Note in this context that these three hypotheses are not

Table 1
Predictions deriving from three possible mechanisms (attentional engagement, attentional disengagement, covert attention) underlying distractor interference effects in singleton feature search

	Attentional-engagement hypothesis	Attentional-disengagement hypothesis	Covert-attentional hypothesis
Fixation location	Number of salient distractor fixations > number of target fixations	Number of salient distractor fixations = number of target fixations	Number of salient distractor fixations = number of target fixations
Fixation duration	Duration of salient distractor fixations = duration of 'neutral' distractor fixations	Duration of salient distractor fixations > duration of 'neutral' distractor fixations	Duration of salient distractor fixations = duration of 'neutral' distractor fixations
Latency of first saccade	Latency on salient distractor trial = latency on no-distractor trial	Latency on salient distractor trial = latency on no-distractor trial	Latency on salient distractor trial > latency on no-distractor trial

The gray fields represent the dependent measure (fixation location, fixation duration, latency of first saccade) for which a given mechanism would make quantitatively different predictions relative to the other two mechanisms.

mutually exclusive (e.g., if the first saccade is delayed due to covert competition, it may not be directed to the distractor, but rather straight to the target location if the competition is resolved in favor of the latter).

Some of the above mechanisms that may underlie the distractor interference effect have already been examined in prior studies (e.g., Olivers, Meijer, & Theeuwes, 2006; Theeuwes, De Vries, & Godijn, 2003). For example, Theeuwes et al. (2003) found that the eyes moved as often in the direction of the salient distractor as in that of the target (38% each). However, this large proportion distractor saccades was observed only when the target-defining features were variable across trials (i.e., when the target could be either a red or a green circle or a diamond, as in Theeuwes, 1991). In contrast, when the target-defining features were kept constant across trials (i.e., when the target was always a green circle, as in Theeuwes, 1992), only 1.5% of initial saccades were made in the direction of the singleton distractor, as compared to 67% in the direction of the target. Interestingly, in both conditions, the presence of singleton distractors led to a slowing of RTs, which led Theeuwes et al. (2003) to conclude that interference effects from singleton distractors result largely from attentional capture (covert-attention hypothesis) rather than oculomotor capture (attentional-engagement hypothesis); and, when observers are able to top-down guide attention to particular target features, oculomotor capture does not occur.

However, in all their experiments, Theeuwes et al. (2003) compared RT and oculomotor performance between trial blocks containing 0% versus 100% distractors, with the latter providing maximum incentive for observers to suppress distractors and perhaps eye movements. Thus, it remains a possibility that capture of the eyes does occur even when the target features remain constant, given that distractors are presented on only a minority of trials so that observers have less incentive to suppress them. This issue was addressed in the present study by requiring observers to consistently search for a green circle, however under conditions of a variable proportion of distractor to no-distractor trials.

3. Method

3.1. Participants

Ten observers participated in the experiment (six females; mean age: 23.8 years; all reported normal or corrected-to-normal visual acuity and color vision). All observers were naïve as to the purpose of the study, and gave informed consent prior to their participation. They were paid at a rate of Euro 8.00 (~US$ 11) per session.

3.2. Apparatus

The experiment was conducted in a dimly lit laboratory to minimize reflections on the monitor. Stimulus presentation and RT measurement were controlled by a PC (a 266 MHz Pentium II). The experimental control software was purpose-written in C++. Stimuli were presented on a 17-in. color monitor (at a frame rate of 85 Hz), with a resolution of 1024×768 pixels. Observers viewed the monitor from a distance of 60 cm. They responded to the horizontal or vertical orientation of a single line within the target element by pressing the left and, respectively, right buttons of a response box connected via the serial port to the PC. Eye movements were recorded using an SMI Eyelink system (SR Research Ltd., version 2.01), with 250-Hz temporal and 0.2° spatial resolution, in combination with a chin rest.

3.3. Stimuli

The stimulus display consisted of nine elements that were equidistantly arranged around the circumference of an imaginary circle (of radius 7.25° of visual angle). All non-target elements were green diamonds. The form-defined target (present on each trial) was a green circle. The color-defined distractor (if present) was a red diamond replacing a green non-target diamond. The size of the stimulus outline frames was 2.4° (maximum extension); the luminance of the green and red outline frames was matched: 9.3 cd/m^2. All stimulus outline frames contained a small black line (0.3° in length, 0.17 cd/m^2 in luminance) which was randomly presented in horizontal or vertical orientation. The background was gray (8.2 cd/m^2). The diameter of the black fixation circle (0.17 cd/m^2), presented in the display center at the start of a trial, was 0.7°. The minimum distance between the singleton target and distractor, if present, was 9.3° (i.e., they were separated by at least two items).

3.4. Design and procedure

The experiment consisted of 420 trials, with 140 trials for each distractor condition (20%, 50%, 80%). Each trial started with the presentation of a fixation circle, for 500 ms, in the center of the monitor. Observers were instructed to fixate the circle. Thereafter, the search display was presented

until observers responded, as fast and accurately as possible, to the orientation of the single line inside the (form) target. Observers were not explicitly instructed to make an eye movement to the singleton target. However, to ensure that they would make eye movements, (1) the response-critical line presented inside the target singleton was small (0.3° of visual angle) and (2) stimuli appeared relatively far away from the display centre (eccentricity of 7.25°). The inter-trial interval was 1000 ms following correct-response trials, and 2000 ms after error trials.

The experiment was run in two sessions, separated by a break of at least one hour (but not more than 2 days). Within a given session, half of the observers performed first the 20%-distractor condition, followed by 50%- and 80%-distractor conditions and vice versa for the other half. This order of blocks was held constant across the two groups and sessions. Each session consisted of 6 blocks with 3 (unrecorded) warm-up plus 32 experimental trials. The blocks were separated by a break to recalibrate the eye tracker. Within a given block (20%-, 50%-, 80%-distractor conditions), distractor and no-distractor trials were randomly intermixed with each other. At the beginning of the first session, observers practiced the experimental task in two blocks (50%-distractor condition) of 35 trials each (RT and oculomotor measures not recorded).

4. Results

Data analysis was done using Ihaka & Gentlemen (1996). Trials on which a response error was made (overall 3.2% of all trials; see accuracy results below) were eliminated prior to RT and eye movement analysis. Furthermore, trials on which no eye movements occurred (i.e., if the eyes remained at the central fixation circle) or on which eye movement data were (partly) lost owing to blinks were also excluded from analysis (in total, 15.4% of the trials).[1] In addition, for each observer and experimental condition, RTs 2.5 standard deviations above or below the mean were discarded as outliers (overall, 2.3% of the trials). Using EyeLink's 2.01 default configurations, eye movements were classified as saccades if their speed exceeded 35°/s and their acceleration 9500°/s^2. The first saccade was defined as the first eye movement landing outside the diameter of the fixation circle (0.9°).

4.1. Reaction time

Fig. 1 presents the group mean correct RTs, along with the error rates, as a function of distractor condition (20%, 50%, 80%), separately for distractor and no-distractor trials. RTs were examined by a repeated-measures analysis of variance (ANOVA) with two factors: distractor condition (20%, 50%, 80%) and trial type (distractor trial, no-distractor trial). This ANOVA revealed the main effect of trial type to be significant [$F(1,9) = 40.68$, $p < .01$, MSE = 367.41]: RTs were overall slower on distractor than on no-distractor trials (731 vs. 700 ms). The main effect of distractor condition was not reliable. However, importantly, the distractor condition × trial type interaction was significant [$F(2,18) = 5.18$, $p < .01$, MSE = 567.28]. As confirmed by post hoc Tukey LSD tests, RTs were slower on distractor relative to no-distractor trials in the 20%- and 50%-distractor conditions (20%-distractor condition: 757 vs. 701 ms; 50%-distractor condition: 727 vs. 695 ms), but not the 80%-distractor condition (710 vs. 703 ms).

Note that the effects of distractor proportion were relatively balanced between the two groups of observers: observers performing the distractor conditions in ascending (20%–50%–80%) or descending order (80%–50%–20%) exhibited overall interference effects of 29 and 34 ms, respectively [one-tailed $t(8) = 1.85$, $p > .30$]. However, in the 20%-condition, the interference effect was larger for the group that started with 20% rather than 80% distractors [73 vs. 38 ms; one-tailed $t(8) = 1.85$, $p < .05$]. In contrast, in the 50%- and 80%-conditions, the interference effects were not significantly different between the two groups of observers [50%-condition: 15 vs. 49 ms, $t(8) = 1.85$, $.10 > p > .05$; 80% condition: −1 vs. 15 ms, $t(8) = 1.85$, $p > .10$]. This pattern suggests that distractor interference is modulated by both observers' opportunity to acquire and their incentive to apply an effective suppression strategy (a point systematically elaborated by Müller, Geyer, Zehetleitner, & Krummenacher, 2008, in a study in which both the initial experience with distractors and the incentive to apply distractor suppression was factorially varied in a between-subject design).

Furthermore, note that Theeuwes (1992) found significant distractor interference even when distractors were presented in 100% of the trials, while there was hardly any interference when distractors were frequent (80%) in the present experiment. One possible explanation for this apparent discrepancy might derive from the fact that RTs in the present experiment (716 ms) were overall slower than those in Theeuwes' study (<600 ms)—since the magnitude of interference has been reported to depend on response speed, with greater interference for faster responses (van Zoest, Donk, & Theeuwes, 2004). In order to look for such an effect in the present data, the magnitude of interference was re-examined separately for fast and for slow responses (based on a median split). As of most interest, when distractors occurred in the majority (80%) of trials, there was a significant distractor interference effect of 15 ms for fast responses [one-tailed $t(8) = 1.85$, $p < .05$], but no interference when responses were slow (effect of −1 ms). Importantly, however, even with fast responses, interference effects were modulated by the frequency with which distractors were presented: interference was the larger the higher the proportion of distractors (55, 32, and 15 ms with 20%, 50%, and 80% distractors, respectively). Thus, the overall non-significant distractor interference effect with frequent distractors is likely to be related to the fact that RTs were overall relatively slow in the present experiment.

[1] When the eyes remained at central fixation, error rate was greatly increased compared to when the eyes left the display center [31.9% vs. 3.2%, one-tailed $t(9) = 1.83$, $p < .01$]. Given that chance level performance was 50%, this large error rate is likely to reflect the fact that overt shifts of the eyes were required to successfully discriminate the orientation of the line within the target shape.

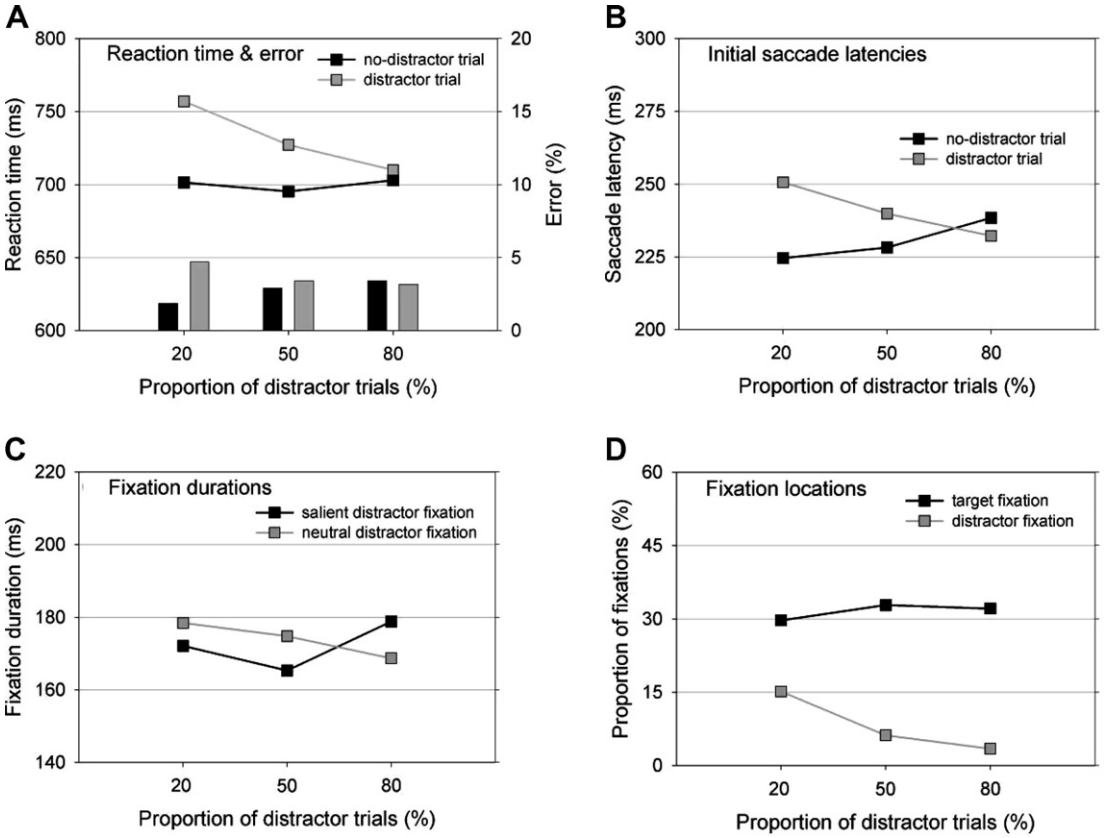

Fig. 1. Reaction times (RTs) and oculomotor performance as a function of distractor condition (20%, 50%, 80%). (A) Mean correct RTs (compare lines with left *y*-axis) and error rates (compare bars with right *y*-axis), separately for distractor (gray lines) and no-distractor trials (black lines). (B) Mean first-saccade latencies on distractor (gray) and no-distractor trials (black). (C) Mean durations of initial fixations at neutral (black) and singleton distractor locations (gray). (D) Proportions of initial saccades directed towards singleton targets (black) and distractors (gray).

4.2. Response accuracy

Observers' individual error rates ranged between 1.0% and 7.9%. The error rates were analyzed by an ANOVA with distractor condition (20%, 50%, and 80%) and trial type (distractor trial, no-distractor trial) as factors. This ANOVA revealed a main effect of trial type [$F(1,9) = 6.73$, $p < .05$, MSE = 2.28], due to an overall larger number of errors on distractor than on no-distractor trials (3.7% vs. 2.8%). Although there was a tendency for this effect to decrease when the proportion of distractors increased, the interaction between the two variables only approached significance [$F(2,18) = 2.37$, $.05 < p < .15$, MSE = 5.41]. This pattern of error effects argues against speed-accuracy trade-offs determining RT performance.

4.3. Oculomotor performance

The initial eye movements away from the display center were classified as target fixations when they landed on the target location or one location adjacent to it (5.0°), as distractor fixations when they landed on the distractor location or one location adjacent to (5.0°), or else as other fixations.

Fig. 1 presents also the eye movement parameters—proportion of target and distractor fixations, fixation duration, and latency of the first saccade—separately for the three distractor conditions.[2] The first-saccade latencies were examined by a distractor condition (20%, 50%, 80%) × trial type (distractor, no-distractor) ANOVA. This ANOVA revealed neither the main effect of distractor condition nor that of trial type to be significant, but their interaction was reliable [$F(2,18) = 4.74$, $p < .05$, MSE = 274.05]. As confirmed by post hoc tests, latencies were significantly longer on distractor than on no-distractor trials in the 20%-distractor condition (251 vs. 225 ms; $p = .01$), but not the 50%- and 80%-distractor conditions (50% distractors: 240 vs. 228 ms; $p = .13$; 80% distractors: 238 vs. 232 ms; $p = .41$).[3]

The two other dependent parameters—fixation duration and fixation location—were analyzed in two further ANOVAs. For fixation durations, the independent variables were distractor type (at salient distractor, at neutral dis-

[2] Because there were no reliable differences in the proportion of target fixations between distractor and no-distractor trials [20%-distractor condition: 28.5 vs. 30.9, $t(9) = 2.26$, $p = .47$; 50%-distractor condition: 30.6 vs. 35.1%, $t(9) = 2.26$, $p = .21$; 80%-distractor condition: 31.1 vs. 33.1%, $t(9) = 2.26$, $p = .60$], the proportions of target fixations in this and the following analyses were averaged across the two types of trial.

[3] Because of the small number of first saccades directed to the singleton distractor (only on some 4 trials in the 20% distractor condition in which the proportion of such saccades was highest), the latencies of the first saccade were not analyzed further according to where the saccade was directed (target vs. distractor location).

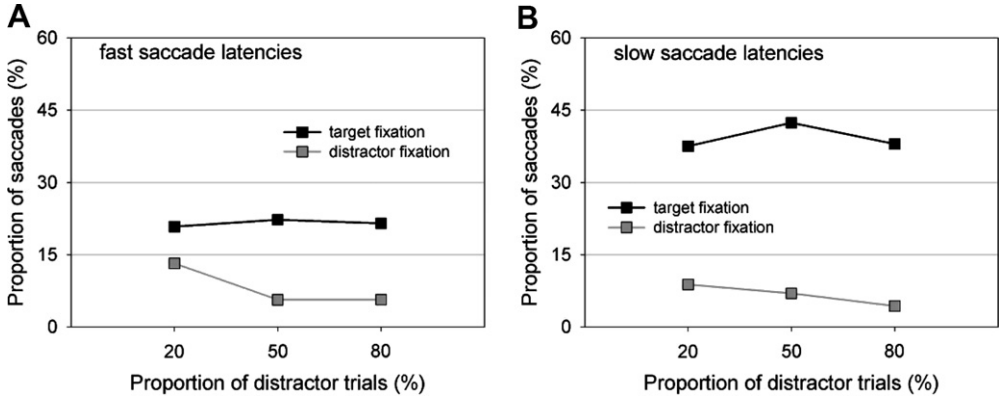

Fig. 2. Proportion of first saccades towards target (black) and distractor singletons (gray) as a function of distractor condition (20%, 50%, 80% distractors), separately for fast (A) and slow (B) first-saccade latencies.

tractor) and distractor condition (20%, 50%, 80%). This ANOVA did not reveal any significant effects.

For fixations, the independent variables were fixation location (on target, on distractor) and distractor condition (20%, 50%, 80%). This ANOVA revealed the fixation location main effect [$F(1,9) = 74.49$, $p < .01$, $\mathrm{MSE} = 109.16$] and the distractor condition × fixation location interaction [$F(2,18) = 3.54$, $p < .05$, $\mathrm{MSE} = 82.18$] to be significant. The main effect of fixation location occurred because an overall larger proportion of fixations were made on the target rather than the distractor singleton (31.5% vs. 8.3%). Furthermore, as indicated by the significant interaction, while the proportion of target fixations was little affected by the distractor condition (29.7%, 32.8%, and 32.1% in the 20%-, 50%-, and 80%-distractor conditions, respectively), distractor fixations occurred more frequently with 20% distractors (15.2%) than with 50% (6.2%; 15.2% vs. 6.2%, $p < .05$) and 80% distractors (3.4%; 15.2% vs. 3.4%, $p < .01$); between the 50% and 80% conditions, the difference in the proportion of distractor fixations was non-significant (6.2% vs. 3.4%, $p = .50$).

Furthermore, fixation locations were re-analyzed dependent on the latency of the first saccade. Concerning this analysis, Theeuwes et al. (2003; Experiment 2) had found observers to make slightly fewer eye movements towards the target singleton with short (compared to long) saccade latencies. That is, with short-latency saccades, part of the distractor interference may be attributable to an increased proportion of fixations towards the singleton distractor (and a decreased proportion towards the singleton target). To examine this, initial-saccade latencies were first classified as short versus long (based on a median spilt); next, the proportions of target- and distractor-directed eye movements were determined for both the short- and the long-latency saccades. These proportions (see Fig. 2) were then examined—separately for target- and distractor-directed saccades—by an ANOVA with the factors saccade latency (short, long) and distractor condition (20%, 50%, 80%).

The ANOVA of initial target-directed saccades revealed (only) the main effect of saccade latency to be significant [$F(1,9) = 18.65$, $p < .01$; $\mathrm{MSE} = 253.83$]: an overall smaller proportion of initial eye movements was directed to the target when saccade latency was short rather than long (21.5% vs. 39.3%), and this was relatively independent of the distractor condition (short latencies: 20.8%, 22.2%, and 21.5%; long latencies: 37.5%, 42.4%, and 38.0% in the 20%-, 50%-, and 80%-distractor conditions, respectively). The ANOVA of distractor-directed saccades revealed (only) the main effect of distractor condition to be significant [$F(2,18) = 4.65$, $p < .05$; $\mathrm{MSE} = 42.72$]: a significantly larger proportion of initial saccades was made to the singleton distractor when distractors occurred in 20%, as compared to 50% and 80%, of the trials (14.8% vs. 6.3% and 5.0%; both p's $< .05$), and this was relatively independent of the latency of the first saccade being short or long (short latencies: 17.0%, 5.6%, and 5.7%; long latencies: 12.6%, 7.0%, and 4.4%). This pattern of results argues that, one the one hand, fast oculomotor responses were generally less selective (in that fewer saccades were immediately directed to the target compared to slower responses); on the other hand, specific distractor interference (with a singleton distractor initially attracting an eye movement) was stronger when distractors were rare (20%), with a tendency for the interference to be reduced with long compared to short saccade latencies (12.6% vs. 17%).

In summary, first-saccade latencies were influenced more markedly when distractors appeared in a small proportion (20%) of trials, as was the percentage of eye movements directed to the distractor singleton (though even under this condition, more eye movements were made overall towards the target singleton [29.7% vs. 15.2%; one-tailed $t(9) = 1.83$, $p < .01$]). The longer first-saccade latency on distractor trials in the 20%-distractor condition is likely to reflect covert competition of the distractor with the target for attracting focal attention (26-ms effect). This competition was significantly reduced when distractors were more likely to appear (12- and 6-ms effects in the 50%- and 80%-distractor conditions). Consistent with this pattern of first-saccade latencies, in the 20%-distractor condition, the distractor was relatively more likely to attract an eye movement (only 14.5% more

target than distractor fixations), compared to the 50%- [26.6%; 14.5% vs. 26.6%, one-tailed $t(9) = 1.83$, $p < .05$] and 80%-distractor conditions (28.7%; 14.5% vs. 28.7%, one-tailed $t(9) = 1.83$, $p < .05$]. Again, this argues that that the distractor was more 'competitive' for focal attention under the 20%-distractor condition.

4.4. Cross-trial effects

To further explore the micro-structure of the interference effect, the trial N (distractor, no-distractor) RT and oculomotor performance were re-analyzed depending on the presence or absence of a singleton distractor on the preceding trial $N-1$. Specifically, RTs and oculomotor measures were analyzed in terms of four different cross-trial ($N-1 \rightarrow N$) transition conditions: a no-distractor trial following a no-distractor trial (no → no); a distractor trial following a no-distractor trial (no → yes); a no-distractor trial following a distractor trial (yes → no); and a distractor trial following a distractor trial (yes → yes). It was hypothesized that, if the magnitude of distractor interference is modulated by observers' incentive to suppress distractors, then the suppression/inhibition should also become manifest across trials, with the interference effect being smaller for transitions in which a distractor was present on trial $N-1$ compared to transitions in which a distractor was absent on trial $N-1$. This is expected because, following the need to suppress a distractor on trial $N-1$, more reactive top-down control is recruited to shield against distractor interference on the following trial N (e.g., Botvinick, Braver, Barch, Carter, & Cohen (2001), Kerns et al. (2004))[4] or the suppression strategy remains in a state of activation. Importantly, this pattern should be less pronounced when distractors are presented in a high rather than a small proportion of trials (e.g., 80%- as compared to 20%-distractor condition), because of observers' overall higher incentive to suppress distractors in the former condition (e.g., they generally invest more top-down control or have a suppression strategy more readily available).[5]

Fig. 3 presents the trial N distractor interference effects—separately for the manual RTs and the first-saccade latencies and landing positions (fixation locations)—as a function of distractor condition, dependent on the presence versus the absence of a distractor on trial $N-1$. Interference (on trial N) with a distractor present on trial $N-1$ was assessed by subtracting the RT and oculomotor measures in the yes → no transition from performance in the yes → yes transition; and interference with a distractor absent on trial $N-1$ was assessed by subtracting the RT and oculomotor measures in the no → no transition from the measures in the no → yes transition. To examine how the inter-trial history affects these interference effects, post hoc tests were conducted, based on a separate ANOVA for each of the three interference parameters (RT, saccade latency, and fixation location) with distractor condition (20%, 50%, 80%) and trial $N-1$ (distractor trial, no-distractor trial) as factors.

In terms of RT, the distractor interference (on trial N) was overall larger when a distractor was absent on trial $N-1$ relative to when it present (48 vs. 10 ms; $p < .05$), but this effect diminished with increasing distractor frequency. That is, interference following $N-1$ no-distractor trials was overall larger in the 20%- compared to the 50%- and 80%-distractor conditions (90 vs. 34 and 18 ms, both p's $< .05$), with the 20% condition also exhibiting the most pronounced reduction in interference when a distractor was present on trial $N-1$ (30-ms interference; 90 vs. 30 ms, $p < .05$). By contrast, with 50% and 80% distractors, the differential interference between $N-1$ no-distractor and distractor trials was substantially reduced (50% distractors: 34 vs. 13 ms; $p = .50$; 80% distractors: 18 vs. −14 ms, $p = .31$).

An additional analysis was conducted to test for any longer-range (cumulative) inter-trial effects beyond trial $N-1$ (e.g., Geyer, Müller, & Krummenacher, 2007; Majlkovic & Nakayama, 1994). Assuming the existence of such effects, the reduced inter-trial effects in the 50%- and 80%-conditions relative to the 20%-condition may be attributable to differences in the frequency of a distractor presented on, say, trial $N-2$.[6] To examine this possibility more directly, for the 50%- and 80%-conditions, the trial N RTs in the theoretically important yes → no and yes → yes cross-trial transition conditions ($N-1 \rightarrow N$) were re-analyzed as a function of a distractor being absent versus present on trial $N-2$. This analysis was limited to the influence of trial $N-2$ because there were too few observations for preceding trials $N-3$, $N-4$, etc. to permit statistical analysis. If longer-range inter-trial effects had been operating in the present experiment, then interference effects in the 50%- and 80%-conditions (as assessed by subtracting RTs in the yes → no transition from RTs in the yes → yes transition) should be reduced for trial $N-2$ distractor relative

[4] This prediction derives from the conflict monitoring theory of Botvinick et al. (2001), who assume that, in the case of a response conflict, the anterior cingulate cortex (ACC) signals an increased demand for cognitive control, which leads to an enhanced mobilization of top-down control on the next trial, presumably mediated by the dorsolateral prefrontal cortex. This model predicts less interference from distracting sources of information on trials following a response conflict, because of "high conflict on incongruent trials leading to the recruitment of greater cognitive control on the subsequent trial" (Kerns et al., 2004, p. 1024).

[5] The distractor frequency effects in the present experiment (in particular, the increased interference with a distractor proportion of 20% distractors) are unlikely to reflect passive perceptual learning or adaptation processes, with rare distractors capturing attention due to their 'novelty' relative to the standard stimulus environment (e.g., Neo & Chua, 2006). Müller et al. (2008) have shown that interference effects emerging from rare, 'novelty' distractors (e.g., colored blue amongst green items) are relatively small when observers are encouraged to adopt a distractor suppression strategy by the presentation of a frequent distractor (e.g., colored red).

[6] This account for the pattern of inter-trial effects was suggested to us by an anonymous reviewer.

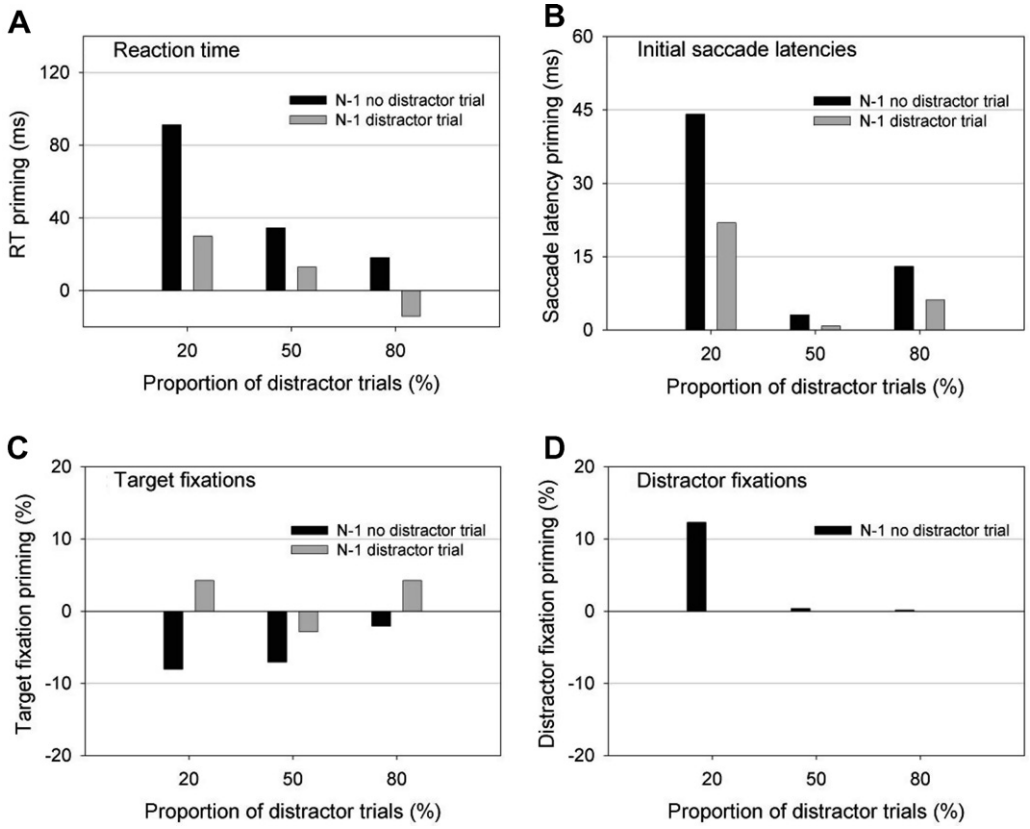

Fig. 3. Cross-trial performance as a function of distractor condition (20%, 50%, 80% distractors). (A) Trial N RTs following $N-1$ distractor (gray bars) and no-distractor trials (black bars). (B) Trial N first-saccade latencies following $N-1$ distractor (gray) and no-distractor trials (black). (C) Trial N proportion of target fixations following $N-1$ distractor (gray) and no-distractor trials (black). Negative values indicate that the probability with which a target is fixated on trial N is decreased if this trial was preceded by an $N-1$ no-distractor, as compared to a distractor, trial. (D) Trial N proportion of distractor fixations following an $N-1$ no-distractor trial. Positive values indicate that the probability with which a distractor is fixated on trial N is increased if this trial was preceded by an $N-1$ no-distractor, as compared to a distractor, trial.

to no-distractor trials. However, for both the 50%- and 80%-conditions, $N-1 \rightarrow N$ cross-trial transition RTs were uninfluenced by the presence versus the absence of a distractor on trial $N-2$: collapsed across the two conditions, the reduction in interference with $N-1$ distractor (yes → yes) relative to $N-1$ no-distractor trials (no → yes) was 27 ms (−2 vs. 25 ms) when there was no distractor on trial $N-2$, and 29 ms (0 vs. 29 ms) when there was a distractor). This argues against the existence of longer-range influences that could reflect automatic (passive) adaptation processes to the presence of a distractor, and in favor of observers exerting enhanced on-line (top-down) control on trial N as a result of encountering a distractor on the immediately preceding trial $N-1$.

A similar pattern of interference effects as for the RT analysis (see above) was revealed for saccade latencies: the distractor-associated delay in producing the first saccade (on trial N) was overall larger when a distractor was absent on trial $N-1$ relative to when it present (21 vs. 9 ms, $.10 > p > .05$). With 20% distractors, the interference was larger compared to 50% and 80% distractors (44 vs. 3 and 13 ms; both p's $< .05$), as was the reduction in interference when a distractor was present on trial $N-1$ rather than absent (20% distractors: 21 vs. 44, $p < .05$; 50% distractors: 1 vs. 3 ms, $p = .90$; 80% distractors: 6 vs. 13 ms, $p = .70$).

Two further ANOVAs were conducted on the proportion of target and distractor fixations (the latter including only the no → yes and yes → yes transitions, with distractor effects estimated by subtracting the proportion of distractor fixations in the yes → yes from that in the no → yes transition). Concerning target fixations, overall more first fixations landed on the target (on trial N) when there was a distractor on trial $N-1$ compared to when there was not one (1.8% vs. −5.7%, $.10 > p > .05$; the negative value indicates that the absence of a distractor on trial $N-1$ reduced the probability with which the target was fixated on trial N). Furthermore this relative increase in target fixations when a distractor was present rather than absent on trial $N-1$ was particularly pronounced in the 20%-distractor condition (20% distractors: 4.2% vs. −8.1%, $p < .05$; 50% distractors: −7.0% vs. −2.9%, $p = .46$; 80% distractors: −2.1 vs. 4.2, $p = .48$). Similarly, significantly more first fixations were made on the distractor (on trial N) when there was no distractor on trial $N-1$ compared to when there was one, but this relative increase was evident only when the distractor proportion was low (12.3% vs. 0.4% and 0.1% for the 20%-, 50%-, and 80%-dis-

tractor conditions; both p's $< .05$; positive values indicate that the absence of a distractor on trial $N-1$ increased the probability with which the distractor was fixated on trial N).

5. Discussion

Distractor interference, in terms of both RT and oculomotor performance, was observed only, or most markedly, when the distractors appeared on a small (20%) relative to an intermediate (50%) or high proportion (80%) of trials. This result only partly confirms previous findings (e.g., Theeuwes, 1991, 1992), which had been taken to suggest that salient color singleton distractors automatically (i.e., invariably) capture attention. The automatic-capture account assumes that attentional priority is regulated entirely by bottom-up factors, that is, stimulus salience. Applied to the present findings, this account would suppose that a salient color singleton distractor would always interfere with the detection/discrimination of the less salient form singleton target. However, at odds with this proposal, observers were almost perfectly able to ignore the color singleton in the 50%- and 80%-distractor conditions. Additionally, the results of the inter-trial analysis cast doubts on a pure automatic (saliency-based) mechanism of attentional selection. The interference was lowest overall when a distractor trial was preceded by a distractor trial (relative to a no-distractor trial), with a particularly marked reduction in interference in the 20%-distractor condition. That is, attentional capture by the salient singleton distractor was modulated by the carry-over of control settings from one trial to the next (i.e., cross-trial distractor suppression/inhibition), rather than being just dependent on stimulus salience. One possibility for the automatic-capture account to deal with this finding would be to assume that cross-trial distractor inhibition is invoked relatively automatically (e.g., Pinto, Olivers, & Theeuwes, 2005). However, since the detrimental effect resulting from a no-distractor trial $N-1$ was reduced in the 50%- and 80%- relative to the 20%-distractor condition, the notion of 'automatic' inhibition would be inappropriate to explain this pattern of interference effects. Rather, the inhibition appears to be largely under top-down control and modulated by observers' incentive to suppress distractors, with the detrimental effect of a no-distractor trial $N-1$ being larger when observers have less incentive overall to suppress distractors. Thus, taken together, the present set of findings is hard to explain in terms of a pure 'automatic' account of attentional selection. Instead, they are more in line with accounts assuming top-down control of singleton distractor interference. Before discussing these accounts further, it is interesting to consider the results with regard to the possible mechanisms hypothesized to underlie distractor interference in pop-out search and how these may be top-down modulated.

5.1. Sources of distractor interference in pop-out search

The three initial hypotheses—attentional engagement, attentional disengagement, and covert attention—emphasize different mechanisms of how singleton distractors could interfere with target detection/discrimination: (1) more frequent shifts of the eyes towards singleton distractor locations (in relation to the target singleton); (2) more time to process singleton distractors (relative to 'neutral' distractors); or (3) stronger competition between the target and distractor for attentional selection. Although these mechanisms are not mutually exclusive, the present findings rule out extended distractor processing time (i.e., attentional-disengagement hypothesis) as the cause of the interference effects. Instead, the results provide support for the two other mechanisms: competition of the distractor for covert and overt shifts of attention (i.e., attentional and oculomotor capture).

Convergent evidence for this comes from Olivers et al. (2006, Experiment 7), who investigated singleton distractor effects in a dual-task paradigm, comprising of a primary memory and a secondary search task. At the beginning of each trial, observers were presented with a to-be-remembered color probe, followed by the search display containing one form target and, in 100% of the trials, a color singleton distractor. Observers' task was to discriminate a small letter presented inside the target singleton. Following the presentation of the search items (and observers' response), a memory test display (of three differently colored items) was presented requiring observers to choose the to-be-remembered color item. Two types of distractor singleton were used: (1) in 50% of the trials, singleton distractors appeared in same color as the memory item (i.e., relevant distractor condition); in the other 50%, they appeared in a different color (i.e., irrelevant distractor condition). Olivers et al. found that (1) an overall larger proportion of eye movements was made to singleton distractors (whether relevant or irrelevant) relative to the target (56% vs. 23%, respectively); (2) more saccades were made towards relevant than to irrelevant distractors (63% vs. 48%); and (3) the saccade latencies were shorter when the movement was directed to a relevant, rather than an irrelevant, distractor (174 vs. 180 ms). Olivers et al. took these results to indicate that more frequent shifts of the eyes towards (relevant) distractor are a key factor responsible for distractor interference.

While this is generally in line with the present results, there are also noteworthy differences relative to the findings of Olivers et al. (2006). The most striking difference concerns the proportion of saccades made towards target and distractor singletons: In Olivers et al., more fixations were made towards distractor than target singletons (56% vs. 23%); in contrast, in the present study, more fixations were made towards target than to distractor singletons (32% vs. 8%; data averaged across the 20-, 50-, and 80%-distractor conditions), and this was the case even when distractors were presented on only 20% of the trials (30% vs.

15%). One explanation for these discrepant findings may derive from the different types of task used to assess distractor interference: search task only (present study) versus dual-task conditions (Olivers et al.). That is, when distractor (color) information is maintained actively in working memory (as observers were required to do in the experiment of Olivers et al. in order to respond correctly in the memory task), the singleton distractor in the search array may become a very strong attractor for attention (i.e., an even stronger attractor than the singleton target). These task demands may have been responsible for the large proportion of saccades towards (especially relevant) distractors and the small proportion of saccades towards the target, even though distractors were presented on 100% of the trials. Consistent with this, Theeuwes et al. (2003; Experiment 2) found that, under search-task-only conditions, observers were able to ignore the distractor singleton almost perfectly (with a proportion of only 1.5% of saccades towards the distractor).

5.2. Attentional versus oculomotor capture

Theeuwes et al. (2003) proposed that color singleton distractors lead to attentional, rather than oculomotor capture under conditions in which the target-defining features remain constant across trials, so that observers are able to top-down allocate attention to the target dimension. The present experiment was similar to Theeuwes et al., in that observers consistently searched for the same shape target. However, in contrast to Theeuwes et al., color singleton distractors were present on a variable proportion (20%, 50%, or 80%) of trials, rather than on each trial—to manipulate observers' incentive to inhibit the distractor and/or facilitate the target dimension (greater incentive with larger proportion). Thus, assuming that observers are able to top-down modulate the attentional processing of target and distractor singletons, it is possible that under conditions of reduced (incentive for) top-down control (i.e., with 20% distractors), distractors elicit a relatively large amount of eye movements towards their locations, but that under condition of high (incentive for) top-down control (i.e., with 80% or 100% distractors), distractors are fixated only infrequently.

In line with Theeuwes et al. (2003), manual RTs were found to be slowed by the presence of singleton distractors across all distractor conditions (32-ms effect; Theeuwes et al.: 20-ms effect). However, the interference effect was larger when observers had less incentive to suppress distractors (56 ms vs. 32 and 7 ms with 20% vs. 50% and 80% distractors). For oculomotor performance, a larger proportion of eye movements were made overall towards the target rather than the distractor singleton (30 vs. 8%; Theeuwes et al., 2003: 67 vs. 2%). Furthermore, the ratio of target to distractor saccades was modulated by the proportion of distractor trials within a given experimental block, due to distractor-directed saccades occurring more frequently in the 20%-distractor condition (target vs. distractor saccades: 30 vs. 15%) relative to the 50%- and 80%-distractor conditions (30% vs. 6% and 33% vs. 3%, respectively). Taken together, this pattern of RT and oculomotor performance supports the idea that distractor interference is modulated by observers' top-down incentive to suppress distractors. However, although interference in terms of manual RTs was overall largest with 20% distractors, observers in this condition still made twice as many saccades towards the target compared to the distractor singleton. Therefore, as suggested by Theeuwes et al. (2003), when the target-defining features remain constant across trials, distractor interference may indeed be largely attributable to attentional, rather than oculomotor, capture, even when distractors occur on only a small proportion of trials—though, clearly, there is also a component of oculomotor capture contributing to the interference.

5.3. Top-down distractor suppression

While the present results are generally more in line with accounts assuming top-down control of singleton distractor interference, they are not fully compatible with all these accounts. Specifically, Bacon and Egeth's (1994) search mode account assumes that singleton distractors may interfere with target detection only when observers are in singleton detection mode (i.e., when the target is a unique form singleton), whereas singleton distractors may be ignored when observers are in a feature search mode (i.e., when the target is not a unique form element). Thus, given that the conditions of the present experiments were equivalent to those in which Bacon and Egeth observed distractor interference, the observers would have performed the task in singleton detection mode. However, this is at variance with the absence of significant interference when observers encountered a high proportion of distractor trials, in which case one would have to assume that they adopted a feature search mode—even though the target was the only form singleton. Alternatively, one would have to assume that top-down control of singleton distractor interference is possible even when observers operate are in singleton detection mode. These additional assumptions would, however, generally question the explanatory value of any distinction between singleton detection and feature search modes. In any case, the critical question for this account remains why observers were able to 'control' singleton distractor interference even if they were, in terms of Bacon and Egeth, in a singleton detection mode.

Similarly, the contingent-capture account of Folk et al. (1992), with its central notion of attentional control settings, would also fail to fully explain the present data. A strong version of this account would predict that control of the distractor's defining (color) attributes capturing attention should be possible when observers set themselves to the target's defining (form) attributes—irrespective of the ratio of distractor to no-distractor trials. This is at odds with the present data, which revealed a substantial effect of this ratio. One possibility for this account to explain this

effect would be to assume that attentional control settings do not work in an all-or-nothing manner, but rather in a graded fashion (i.e., control of attentional set is possible with 50% and 80%, but not 20% distractors), continuously regulating competing form and color signals to determine the deployment of focal attention. Whatever the answer, the critical question that remains to be answered by this account is why observers were unable to set themselves to the target's form dimension when distractors were presented on only a small proportion of trials.

Overall, the present pattern of results is most consistent with the dimension weighting account (DWA; e.g., Müller et al., 1995, 2003). DWA assumes that, given sufficient incentive, observers can top-down modulate the weight assigned to a given dimension: up-modulate the weight for the target dimension and/or down-modulate the weight for the distractor dimension. This modulation enhances the saliency signal produced by the target at the master map level, while attenuating that generated by the distractor, so that the target is more likely to win the competition for focal attention.

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